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Procedia Engineering 144 (2016) 1060 – 1066

Procedia Engineering

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12th International Conference on Vibration Problems, ICOVP 2015

Thermo-mechanical interlaminar Stress and Dynamic Stability analysis of Composite Spherical Shells

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Abstract

Three-dimensional Finite Element Method (FEM) based thermo-mechanical stress analysis of a laminated Fibre Reinforced Polymer (FRP) composite made spherical shell structure subjected to an elevated thermal filed has been carried out. FE simulation has been carried out through ANSYS 14.0, using Brick 8-node solid 185 layered elements. Shell structures due to curvature effect show thermo-mechanical stress concentration effects not only at the edges but also at various other critical locations in its domain. Appropriate FE mesh size has been adopted to capture these stress concentration effects and has been established through validation with analytical results. Out-of-plane thermo-mechanical interlaminar stresses (σ_{rr}, $\tau_{\theta r}$, $\tau_{\phi r}$) has been assumed to be responsible for damage initiation and hence have been analysed in details in order to reveal the critical ply-interface. In order to study dynamic stability of the shell structure under thermal environment, different lamination schemes have been adopted ($[0/\theta]_4$, $\theta = 0^0, 15^0, 30^0, 45^0, 60^0, 75^0$, and 90^0). It has been observed that, plies oriented parallel to the cantilevered edge of the shell structure are providing minimum deformation under an elevated thermal environment. However, the laminated shell shows a geometrically non-linear behaviour as the ply-orientation angle has been varied.

Peer-review under responsibility of the organizing committee of ICOVP 2015

Keywords: Spherical shell structures, Dynamic stability, Finite element analysis, Interlaminar stresses, Laminated FRP compositesIntroduction

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Peer-review under responsibility of the organizing committee of ICOVP 2015
doi:10.1016/j.proeng.2016.05.058

1.Introduction

The use of FRP made thin spherical shell structures find tremendous applications in fields like aerospace, automobile, defence, civil engineering etc. These structures many a time experience wide temperature changes such as in aircraft structural components and wind turbine blades, etc. These advanced structures have become popular because of its superior properties and the ability to be tailor made to meet design requirement. In order to understand the design aspects and real world behaviour of composite shell structures in depth study is highly essential. As most of the laminated FRP made structure undergo curing, the thermo-mechanical analysis of such composite structures has been an important subject of study. These residual stresses are found to arise due to the significantly higher shrinkage of the matrix compared with the fibres. The magnitude of process-induced residual stress is sufficient to initiate transverse cracks and delaminations. The analysis done by Bogetti et al. [1] suggests that the mechanics and performance of laminates are strongly dependent on curing history. Analytical methods were used by Senel et al.[2] to perform residual stress analysis of laminated composite plates under thermal loads. Shabana and Noda [3] have used finite element method to investigated elasto-plastic thermal stresses in rectangular plate composite functionally graded materials. There effect of lamination scheme was studied by Faruk Sen et al.[4] for symmetric angle-ply laminated thermoplastic composite plates having different square hole dimension under uniform thermal heating. Gigliotti et al.[5] carried out post bucking analysis of composite laminated plates due to thermal loads. He found the out-of-plane displacements; arise by uniform thermal fields in [0º/90º] laminated square plates. Although some work is available for thermo-mechanical analysis of laminated plates but very few works is available for laminated curved panels. Thangaratnam et al. [6] have performed a FEM analysis on post buckling of behaviour laminated cylindrical shells. Dynamic stability and inter-laminar stress analysis of spherical shell structures subjected to mechanical loading has been carried out by Das et al. [7]. But the combined effect of thermal fields affecting structural integrity and dynamic stability still requires proper research and has been addressed in the present work.

2.Specimen geometry and boundary conditions

The composition of the material that has been considered are 8 layered graphite/epoxy (Gr/E) laminated FRP composite having ply configuration $[0]_8$. The composite spherical shell is symmetrical with respect to dimensions (length (a) = breadth (b) = 5000mm, a/b =1). The thickness h = 50 mm, and radius of curvatures R =10,000 mm. has been adopted from Qatu and Leissa et al. [8] such that b/h = 100, b/R = 0.5, as shown in Fig. 1 (a). The composite shell was subjected to cantilevered boundary condition U=V=W=0. The present analysis is done in spherical co-ordinate system with its origin at the center of the sphere of which this shell is a part. The shell structure has been subjected to uniform elevated thermal field which is maintained at the temperature difference of $\Delta T=15^0C$ over room temperature of 25^0C.

The properties of the material for the orthotropic FRP composite used for spherical shell have been given in Table1. These material properties have been adopted from the work of Aditi et al. [10].

Table 1.Material properties (Aditi et al. [10]) of Gr/E laminated FRP composite used for the spherical shell.

Material composition	Material constants
Graphite/ Epoxy laminated FRP composite material properties	E_{11} = 144.23GPa, E_{22} = 9.65GPa, E_{33} = 9.65GPa, $\nu_{12} = \nu_{23} = \nu_{13} = 0.3$ G_{12} = 3.45GPa, G_{13} = 4.14GPa, G_{23} = 4.14GPa $\alpha_{11} = 1.1\times10^{-6}$ /^{0}C, $\alpha_{22} = 25.2\times10^{-6}$ /^{0}C

3.Finite element modeling

For cylindrical shell laminates, layered Brick 8-node SOLID 185 elements have been used to discretize the domain as shown in Fig. 1(a). Each ply has been modeled separately with one element per ply in through the thickness direction. The element has been defined through eight nodes having three degrees of freedom at each node: translations in the nodal x, y, and z directions. The element has plasticity, stress stiffening, large deflection, and large strain capabilities. The default element coordinate system is along global directions. An appropriate mesh size has been selected through convergence study for out of plane interlaminar normal peel stresses (σ_{rr}). The stresses were found on the first ply interface exactly on the cantilevered edge. The stress results have been observed to be converged at mesh size of 100 x 100 x 8 mesh size as shown in Fig. 1 (b).

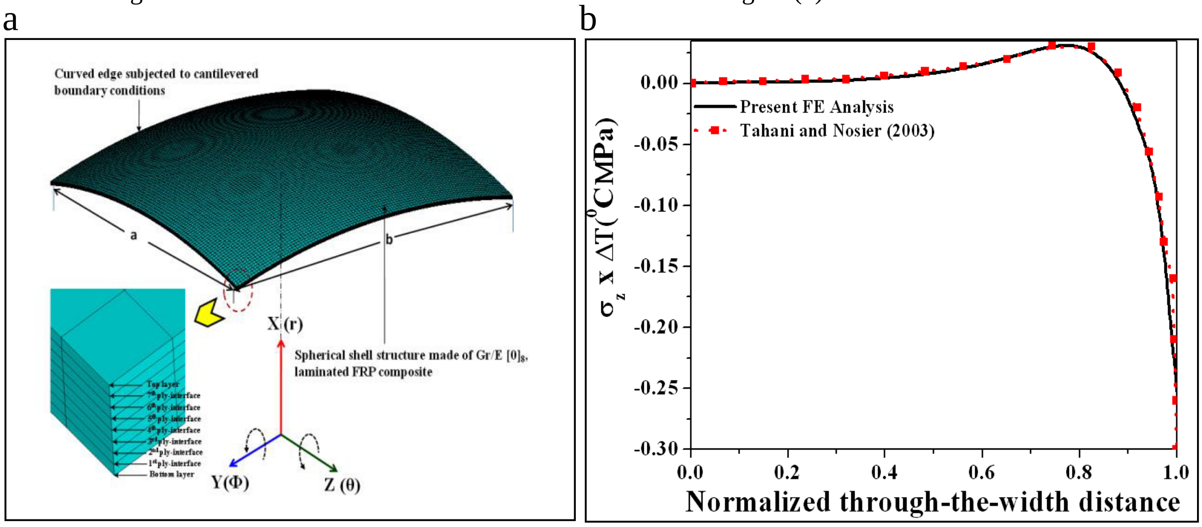


Fig. 1. (a) Finite element meshing of the laminated spherical shell structure Specimen geometry and boundary conditions for the laminated FRP composite (Gr/E $[0]_8$) made for spherical shell laminates) (b) Distribution of through-the-width interlaminar normal stress (σ_z) along [0/90] interface of the Gr/E laminated FRP composite plate with $[0/90]_s$ ply-orientations due to a temperature change (ΔT) of 1^0C (Tahani and Nosier et al.[9]).

4.Results and discussion

The complete three dimensional study of out of plane stresses (σ_{rr}, $\tau_{\theta r}$, $\tau_{\phi r}$) for $[0]_8$ has been discussed in details in the following section.

4.1. Three dimensional stress analysis

The thermo-mechanical stresses are found to exist mostly towards the cantilevered section of the shell structure. The stresses are predominantly of compressive nature (indicated by the negative values) exactly at the cantilevered edge but changes to tensile (indicated by the positive values) abruptly. Furthermore the stresses become almost negligible as we move form cantilevered edge to free edge. These stress concentrations towards the cantilevered edge are not only limited to free edges as in the case of plates, rather due to curvature effect they are also present inside the shell boundary. A through the thickness study for all the seven ply interfaces over inter-laminar stresses reveals that the maximum stress zone shifts from being present at corner edges on 1st ply interface to the midpoint on the 7th ply interface. It is also found that from the stress magnitude point of view that 7th ply interface is the most critical one and hence been discussed in greater detail in the following sections. Peel stress is the most dominant stress out of the three and may also lead to the delamination, a kind of failure generally seen with laminated FRP composites. The distribution of peel stress over the entire 7th ply interface has been shown in the Fig. 2(a). The stress is attaining its maximum value at the midpoint on the cantilevered edge. Also the stress is compressive at the cantilevered edge and changes to tensile as we move towards free edge Fig. 2(b). Out of plane shear stress ($\tau_{\theta r}$) is found to be least contributing as its value is minimum out of the three as shown for 7th ply interface in Fig. 2 (c). A zoomed view of the stress profile shown in Fig. 2 (c) has been represented in Fig. 2 (d) which indicates that there occurs a uneven fluctuation shear stress at the edges. The out of plane interlaminar shear stress ($\tau_{\varphi r}$) has been found to be of somewhat significant as its values are comparable with the values of SRR as shown in Fig. 2(e) also it can be clearly seen that on the 7th ply interface the shell structure is having maximum shear stress at the midpoint and not near the free edges (Fig. 2(f)). The effect of curvature has been found to be maximum for this stress.

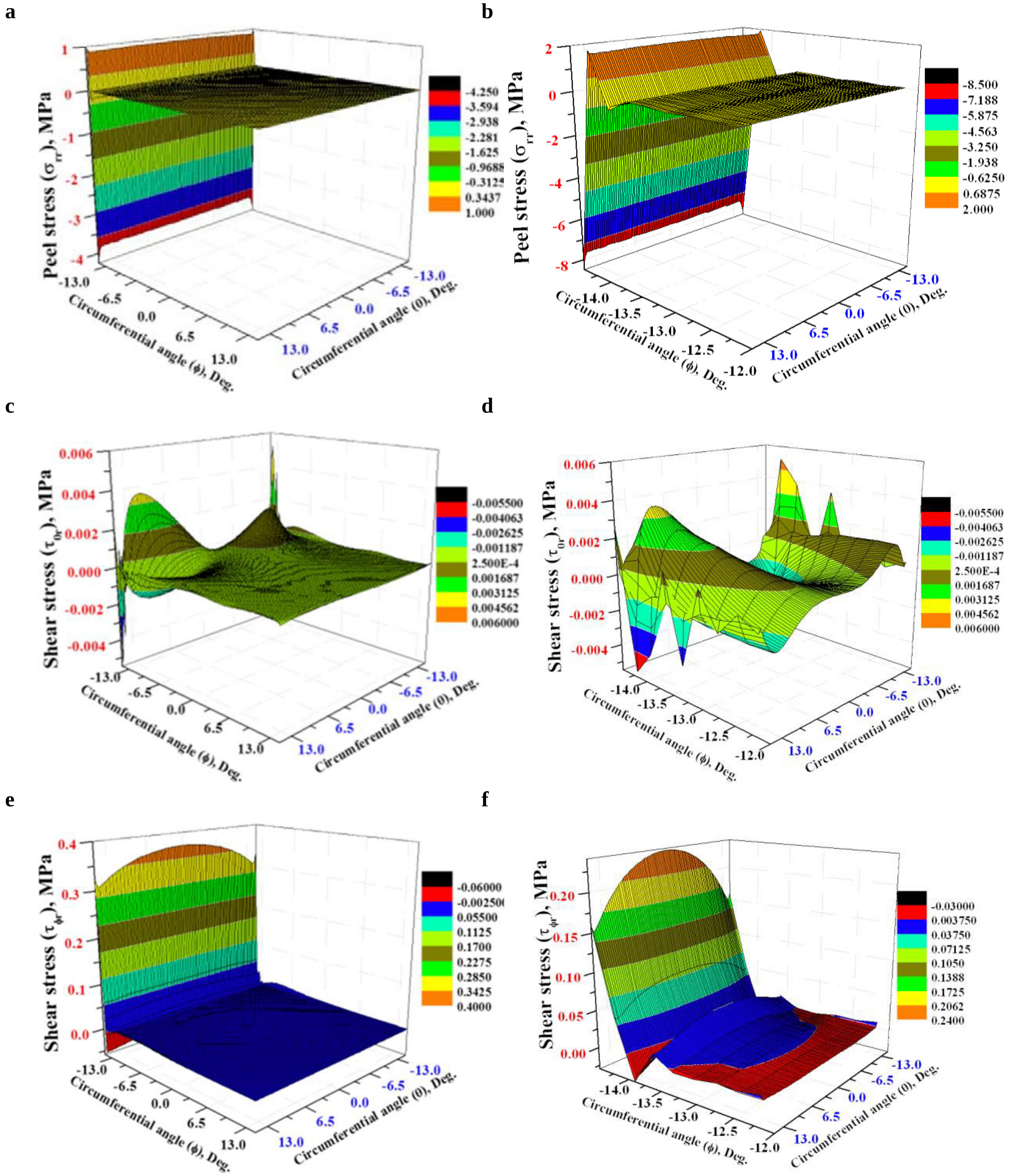
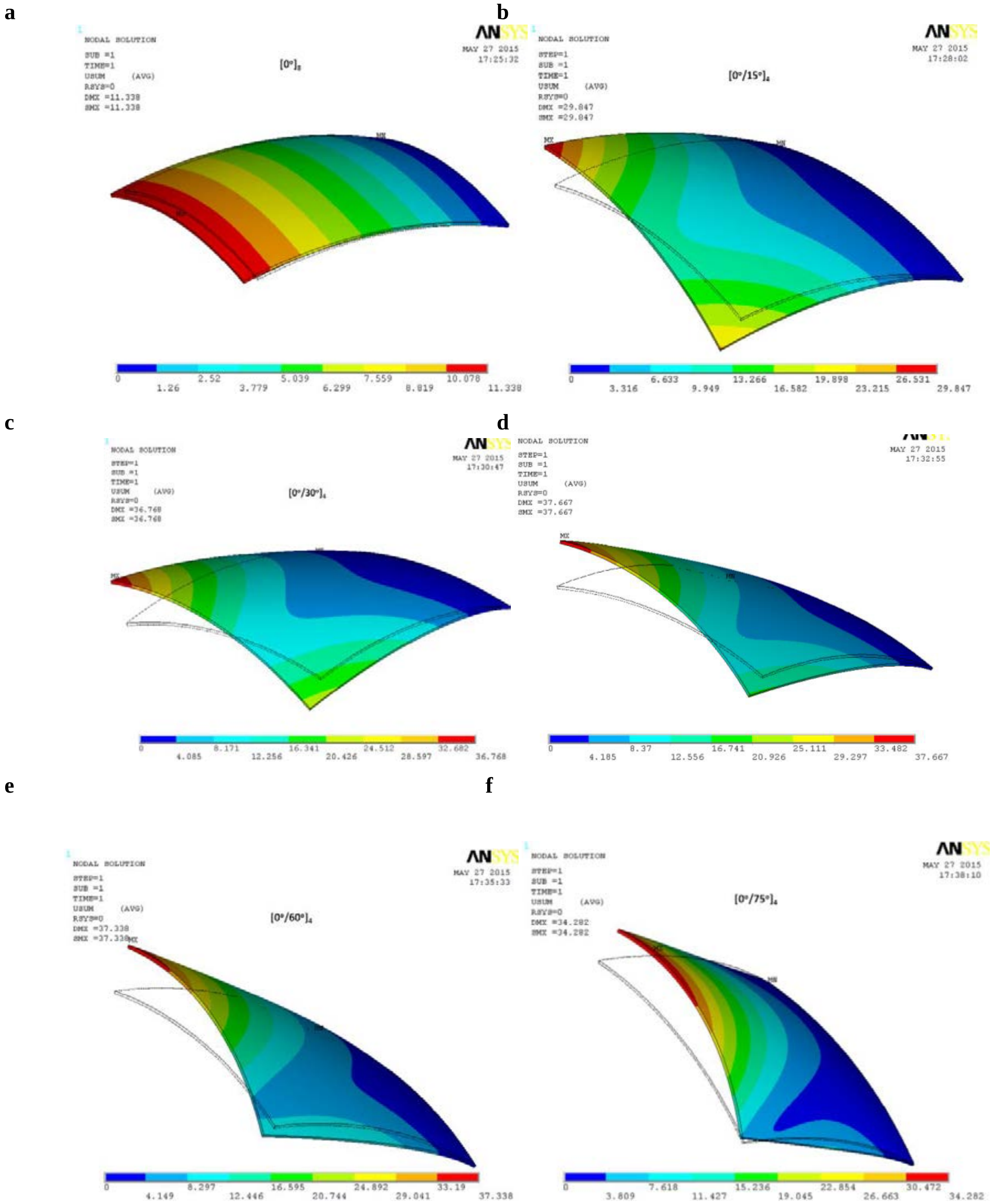


Fig. 2. (a) Three dimensional out-of-plane peel stress (σ_{rr}) distributions at seventh ply-interface of the spherical shell due to a temperature change (ΔT) of 15^0C, (b) Zoomed view near the cantilevered edge (c)Three dimensional out-of-plane shear stress ($\tau_{\theta r}$) distributions at seventh ply-interface. of the spherical shell due to a temperature change (ΔT) of 15^0C (d) Zoomed view near the cantilevered edge (e) Three dimensional out-of-plane shear stress ($\tau_{\Phi r}$) distributions at seventh ply-interface. of the spherical shell due to a temperature change (ΔT) of 15^0C. (f) Zoomed view near cantilevered edge.

4.2. Thermo-mechanical stability of Shell Structure

It is clear that the value of α_{11} and α_{22} for a single ply subjected to elevated thermal field will undergo least deformation in longitudinal direction and maximum in transverse direction.



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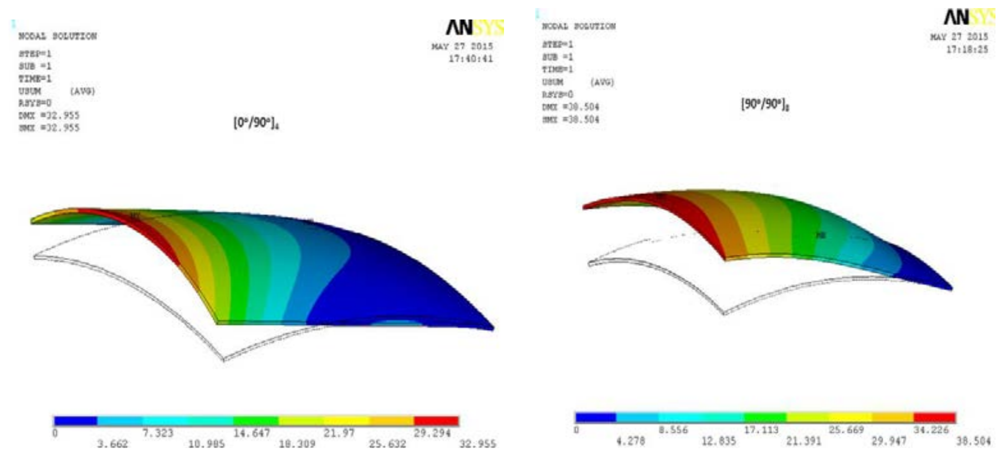

Fig. 3. Total deformation of spherical shell structure by varying its stacking sequence (a). $[0^o]_8$, (b). $[0^o/15^o]_4$, (c). $[0^o/30^o]_4$, (d). $[0^o/45^o]_4$, (e). $[0^o/60^o]_4$,(f). $[0^o/75^o]_4$ (g). $[0^o/90^o]_4$, (h). $[90^o]_8$

Hence the orientation of fibers i.e lamination scheme play an important role in deciding the dynamic stability of composite structures when the undergo curing. The present analysis shows when the fibers are aligned parallel to the cantilevered edge i.e $[0^o]_8$, they undergo minimum deformation and in contrast maximum deformation is found out be occurring for $[90^o]_8$ ply orientation where fibers are aligned perpendicular to the clamped edge as shown in Fig. 3. Gradually the lamination scheme is changed from $[0^o]_8$ to $[90^o]_8$ in the intervals of $[0/\theta^0]_4$ ($\theta = 0^0, 15^0, 30^0, 45^0, 60^0, 75^0, 90^0$). A coupling behavior of bending and twisting is observed with varying lamination scheme. The $[0^o]_8$ ply configuration essentially comprises of bending. The twisting mode starts to increase with changing ply orientation (($\theta = 0^0, 15^0, 30^0, 45^0, 60^0$) and is found to maximum for $\theta = 60^o$ .Further increasing he lamination angle reduces the twisting component and bending components starts to increase again there by giving pure bending deformation for $[0^o/90^o]_4$ and maximum for $[90^o]_8$ is most prominent in, $[0^o/90^o]_4$ and $[90^o]_8$.

5. Conclusions

The complete three dimensional inter-laminar stresses of the shell structure under elevated thermal field reveals many conclusions. Due to curvature effect of the shell structure the stress concentration are not only limited to free edges rather may exist inside the shell boundaries hence care should be taken to select appropriate mesh to capture stress concentrations. These stresses are mostly present towards the cantilevered edge, amongst the three out of plane stresses the peel stress is found be most be dominant followed by ($\tau_{\Phi r}$) and least for ($\tau_{\theta r}$), the through the thickness study of inter-laminar stresses shows a shift of maximum stress zone from occurring at free edges on 1st ply interface to occurring at midpoint on the 7th ply interface.

The stability of shell structure studied through overall deformation of the cantilevered shell structure under elevated thermal field reveals some bending and twisting coupling effects. The structure is found be deforming least for ply configuration $[0^0]_8$ and maximum for $[90^0]_8$ and pure bending components. On changing the ply orientation to angle plies twisting components starts to dominate having maximum value for $[0^0/60^O]_4$ ply orientation. These results may be important from the point of curing where twisting and bending phenomenon may lead to permanent set in the shell structure being cured.

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